U.S. DEPARTMENT OF AGRICULTURE
NATURAL RESOURCES CONSERVATION SERVICE
Minnesota
January 12, 2009

ENGINEERING REPORT

Project: Kellen Grade Stabilization Structure

Location: Big Stone County, Minnesota

Appropriation:
Conservation Technical Assistance
No installation cost share

General Description of Problem or Deficiency. The structure consists of a chute grade stabilization structure lined with articulated concrete block (ACB) tied together with stainless steel cables (Cable Concrete). Some of the concrete blocks have displaced resulting in a partially unlined chute. The lining is a critical component of a chute. Its failure will eventually result in the total loss of the chute and a head cut moving up the waterway.

Authority: Committee Appointment letter from William Hunt, SC, Minnesota dated 9/17/08. The committee was charged to prepare an Engineering Report in accordance with Part 504 of the National Engineering Manual.

Composition of Committee:
Scott Swanberg, Civil Eng., NRCS, St. Paul, MN (Chair)
James Gerding, CET, NRCS, Fergus Falls, MN
Mark Pearson, Agricultural Eng., NRCS, St. Peter, MN
Nathan Stewart, Agricultural Eng., NRCS, Marshall, MN

Investigation
This drop structure was designed under Practice Standard 410, Grade Stabilization Structure. The structure exceeds Minnesota Engineering Job Class V because of a net drop of 7 feet. The chute slope is 14.47% or 3.875:1 (H:V). Side slopes were designed at 2:1. The chute is lined with an articulated concrete block (ACB) product called Cable Concrete. This product comes as a mat of wet cast concrete trapezoidal blocks with stainless steel cables integrally cast into the blocks to form the mat. Different sized blocks are available, this structure used CC-35 sized blocks, which measure 4.5” high with a base 15.5” square and weigh 62.2 lbs each. Drainage area is 1,382 acres divided by roads with culverts.

Chronology:

- 2002 – 2003. Structure designed by Area Office Engineering staff.

- November, 2003. Design was reviewed by the State Office Engineering Section and approved by John Brach, SCE. Design was reviewed by the state office since it exceeded the state criteria for a EJC Class V with a net drop of 7 feet (EJC V limit is 6 feet) and a design discharge of 380 cfs (EJC V limit s 250 cfs).

- October, 2004. The chute was constructed.

- June, 2005. Flow event caused buckling and lifting of block mats in the lower ¼ of the chute slope. Chute was repaired by pulling the mats back in to position and securing with an additional 20 anchors and 60 clamps.

- June, 2008. Flow caused large block displacement in the lower ¼ of the chute slope. This displacement involved breaking of mat and anchor cables. The request for this engineering report was initiated after this event.

The investigating committee met at the Ortonville field office in the morning of October 1, 2008. In addition to the investigating committee the additional people in attendance were:

Krecia Leddy, District Conservationist, NRCS, Ortonville, MN
Paul Bridgland, Area Engineer, NRCS, Marshall, MN
Gary Blough, Civil Engineer, NRCS, Marshall, MN
Gary Hoffman, District Technician, Big Stone Co. SWCD, Ortonville, MN

The chronology of the project was presented including photographs of significant items.

All those in attendance at the morning meeting then visited the site in the afternoon. Anchor locations were marked with spray paint to get an idea of the density of anchors. A cross section survey was taken across the crest of the chute. A tile probe was used to test for voids under the mats. A hole was dug at the upstream end of the chute to determine if the blocks angled downward as a cut off as shown on the drawings.

Observations of the Committee related to the failure are as follows:

- **2005 Damage.** Photos of the 2005 failure show an uneven surface of the blocks downstream of the uplifted mat edge. It appears that the blocks had lifted during the event and were deposited haphazardly afterwards. As evidence by the gaps between mats, it appears that the mats slid downstream.


June, 2005 Block Movement


June, 2005 Block Movement


June, 2005 Block Movement

Repair of the chute was performed by NRCS and SWCD personnel and consisted of dragging the mats back up into position and adding the additional anchors and clamps.

November, 2005
Repaired Chute after June, 2005 Damage

Referring to the above picture, the repaired surface after the 2005 event does not appear uniform. Blocks near the end of the chute appear uneven with some blocks tilting and projecting above the desired uniform plane formed by the tops of correctly placed blocks. This suggests that some movement of the subbase took place and that when the blocks were dragged back into position they conformed to the altered subbase. Water forces on these block protrusions greatly effect the stability of the blocks.

Rainfall causing the damaging flows was recorded at two nearby landowners who participate in the Minnesota Climatological Network (see Hydrology section on page 10).

- **2008 Damage.** The current condition of the chute as caused by the June, '08 flow event is much worse than that from the '05 event. The displacement of the blocks is much greater and some of the 3/16" stainless steel cables connecting the blocks broke. Many of the blocks in the center, lower ¼ of the chute and in the upstream end of the stilling basin have been disturbed.

  Blocks. In place blocks measured 4.5" high. Block literature classifies the blocks as CC35 blocks. The concrete blocks appeared to be in good shape. The stainless steel cables were measured at 3/16" in diameter and were properly centered in the concrete blocks. Many of the cables in the displaced blocks were broken. The broken cables were frayed.

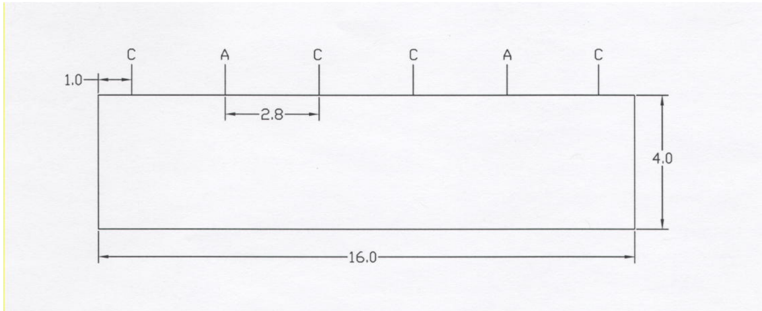
Anchors. Gary Blough stated that during construction the duck billed anchors were driven to their full depth, pulling the concrete mat cables down snug. At first, on the bottom of the chute, they set the anchor by attaching a chain to the cables and pulling up with a back hoe. They stopped setting the anchors further up the chute, thinking that any uplift of the blocks would set them anyway.

The locations of the anchors were marked by the committee using spray paint. They appeared to follow the locations shown on the drawings. Additional anchors placed after the 2005 event were found along the center of the chute. One of the anchor cables at the upstream edge of the detached blocks was able to be pulled out of the ground by a member of the investigating committee. It was in the ground its full length but apparently the cable had been broken. Its end was frayed. We asked those personnel present during construction if this could have been caused during the setting of the anchors. They did not think the damage could have occurred during construction because the broken cable would have been very obvious when the anchor was set.

The anchors still in place appeared to be firmly in place. There is some slack built into the placement of the anchors in that they cannot be driven immediately beneath where they are attached to the mat cables. They are driven in approximately 10" laterally from where they are attached.

In discussion between committee members several methods of attaching anchors to the mats were discussed. The anchor cables on the chute were wrapped around the mat cables and then threaded through the anchor's pig tail before being driven into the ground. Mark Pearson commented that that is how they have installed them in Area 6 and Scott Swanberg mentioned that that is how he observed the anchors on a chute in southern Washington Co., MN. James Gerding said that in Area 2, they use a clamp to attach the two mat cables and the anchor cable. Either method should work acceptably if properly installed. Using the clamp method would help minimize the potential of slack working into the system.

Clamps. There are potential clamping locations on the chute where the additional clamps could have been used. The drawings show four clamps along the 16 ft. side of each mat. If a clamp was placed near each end there is a potential for large gaps to exist between the two remaining clamps. Following the drawings, these gaps should be filled by anchors that would hold the mats together. The drawings do not specify a spacing on the clamps and anchors, but with the end clamps one foot from the ends of the mat, and the remaining clamps/anchors spaced evenly, gaps of 2.8 feet would result between each clamp/anchor.



Assumed Clamp/Anchor Pattern per Drawings

A gap of 2.8 feet between clamps or anchors results in approximately every other block. In observing the uplifted mat in the 2005 event, it appears that an anchor or clamp was missing or that the placement resulted in a greater gap.

There were many other locations where additional clamps or anchors could have been used to secure the mats together. The prescribed clamping pattern allowed slack to develop in the system allowing mats to move.

Potential Clamp/Anchor Location

Block Movement and Potential Clamp/Anchor Location

2008 Displaced Blocks

2008 Displaced Blocks

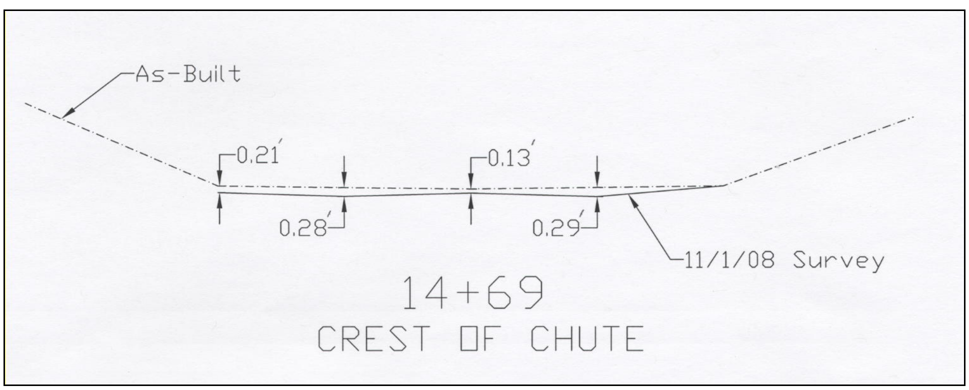
2008 Displaced Blocks,
Broken Stainless Steel Cables

2008 Displaced Blocks

Using a tile probe, approximately three inch deep voids were found under the blocks and geotextile inside of the toes of the chute. These voids started approximately ¼ of the way down the chute and extended to the chute bottom.

2008 Displaced Blocks
Subsidence along RDS toe

A cross section of the chute crest was surveyed and plotted with the as built survey. The site's TBM could not be found so the plotted cross section was adjusted in elevation so that its high point matched the as-built elevation at that point.



The survey documents what was visually apparent, that the crest was not even. The crest had subsided in areas.

<u>Soils</u>. No soils information was found in the design documentation. As part of this investigation, on October 15, 2008, a soil boring was taken next to the inlet section of the chute using a Giddings rig. Samples from the boring are labeled 1-1, 1-2 and 1-3.

Additional samples were taken directly under the blocks half way down the chute using a Back Saver Soil Sampling Probe. The samples were lab classified as follows:

Sample	LL	PI	Lab USCS Classification
1-1	67	40	CH
1-2	65	45	CH
1-3	61	41	CH
Composite 1	60	38	CH
Composite 2	60	38	CH

Table 1

Evaluation

The Committee attempted to:

1. Analyze the Hydrology to determine if the event discharge was within the range of flows that the structure was designed for.
2. Analyze the hydraulics of the structure to compute the velocities and shear stresses experienced during the failure events.
3. Evaluate the Stability of the blocks.
4. Evaluate the subgrade

Hydrology

The original peak flows to the structure site were computed by adding the discharges from four road culverts that control ~1100 acres of the drainage area, to the peak discharge from the lower uncontrolled 282 acres. A type 1 rainfall distribution was used based on guidance used in MN. This guidance was issued 1975 when a study determined that peak discharges computed using NEH Chapter 4 with a type 1 rainfall distribution more closely equaled stream gauge data than that computed using a type 2 distribution. Sonia Jacobsen, Hydraulic Engineer, NRCS, St. Paul, MN was asked to comment on the subject chute hydrology. Sonia commented that the actual rainfall that occurs in MN is a type 2 distribution. The guidance allowing the use of a type 1 distribution was based on the effects of storage in the whole watershed. A more accurate method of computing the peak discharge is to model the watershed using a type 2 distribution and route the hydrographs through culverts to the structure site. Sonia Jacobsen modeled the watershed using WinTR-20. The rainfall amount for the 6/7/05 event is from the maximum of two nearby gauges (0.57" & 2.42"). The rainfall for the 6/11/08 event is from a gauge in the structures drainage area that had just started recording data in 2008. The gauges are maintained by landowners who participate in the Minnesota Climatological Network. Peak discharge results are as follows:

	Q10	Q25	Q100	Q (6/7/05)	Q(6/11/08)
Rainfall, inches	3.9	4.5	5.7	2.42	3.15
Original Hydrology, Type 1, cfs	275	315	380		
WinTR-20 Hydrology, Type 1, cfs	160	197	265	72	115
WinTR-20 Hydrology, Type 2, cfs	225	273	366	101	166

Table 2

The TR-20 modeling with a Type 2 rainfall distribution results in a peak discharge reasonably close to the peak discharges computed in the original design. This is due to the modeling of the watershed, which reduces the discharge from the upper subareas where the runoff is delayed or not contributed due to the culverts and storage areas. This timing of the contributions from subareas changes significantly when modeled as individual subareas.

Peak discharges for the 6/7/05 and 6/11/08 events show that the structure did not experience discharges greater than the structure was designed for.

Hydraulics.
As built cross section and profile data where inputted into the design HEC-RAS computer model along with the peak discharges from the 6/7/05 and 6/11/08 events. A Manning's n value of 0.035 was used in the original design following recommendations of Becker (2003). McCorquodale (1991) recommended for supercritical flow using an n value 0 – 33% greater than those he had computed for subcritical flow. Applying a 33% increase to McCorquodale's recommended n = 0.024 results in n = 0.032 for supercritical flow.

From the HEC-RAS run, the maximum velocities and shear stresses were computed on the chute for the two events using n = 0.032. These are summarized below:

Event	Peak Discharge, cfs	Velocity, ft/sec	Shear Stress, lb/ft^2
6/7/05	101	12.7	6.17
6/11/08	166	14.6	7.39

Table 3

Block Stability
The stability of the mat of blocks needs to focus on the stability of the individual blocks. Any lifting of the blocks from the subgrade creates a void underneath, allowing potential erosive flows against the subgrade and additional forces on the block. Depending on the amount of flow down the chute and the erodibility of the subgrade, the movement of blocks may not mean failure of the entire mat as stresses would be carried by the mats ancillary components consisting of the cables, clamp connectors and anchor system. These ancillary components however should not be factored in the design since their effectiveness is not quantifiable. Flow conditions under an unstable mat are not known, making it difficult to design a non erosive subgrade.

This definition of failure was introduced in Federal Highway Administration (FHWA) RD-89-199 (Clopper 1989) and summarized in NRCS Technical

Supplement 14L. It lists the four following conditions which may lead to this definition of failure:

1. Loss of embankment soil beneath the system by gradual erosion along the slope beneath the system or washout through the system at joints and open cells.
2. Deformation of the underlying embankment through liquefaction and shallow slip failures caused by the ingress of water beneath the system.
3. Loss of a block or group of blocks (uncabled systems) which directly exposes the subgrade to the flow.
4. Flow beneath the ACB causing uplift pressures and separation of the block from the subgrade.

TS-14L goes on to note that:

> Although loss of intimate contact may not lead to total failure of the system, the stability and continued performance of the system has been compromised.

Recommended shear stress limits were developed for the cable concrete mats at the University of Minnesota's St. Anthony Falls Hydraulic Laboratory by Morgan et al (1999). The supplier of the blocks, International Erosion Control Systems, has since lowered these recommended stresses. Documentation as to the lowering of the critical shear stress is not readily available however the values are believable when comparing them to those of other manufacturers.

	Block Size			
	CC20	CC35	CC45	CC70
St. Anthony Falls, Morgan	24.0 lbs/ft2	38.5 lbs/ft2	44.6 lbs/ft2	59.7 lbs/ft2
International Erosion Control Systems		20 lbs/ft2	25 lbs/ft2	31 lbs/ft2

Table 4, Recommended Critical Shear Stresses

The Cable Concrete mats tested at the St. Anthony Falls Hydraulic Laboratory were placed on top of a layer of 7020 Enkamat which was in turn placed on top of a non woven geotextile. 7020 Enkamat is three dimensional mat of polyamide monofilaments approximately ¾" thick that, in this application, acts as a drainage layer. Both NRCS Technical Supplement TS-14L and HCFCD (2001) state that if a drainage layer was used to develop the critical shear stresses of a product, a similar drainage layer should be used in practice. This drainage layer is typically not provided in the construction of these chutes in Minnesota, nor was it provided in the subject chute.

Since these recommended shear stresses are for normal flow type conditions they don't take into account the turbulent forces acting on the block in a hydraulic jump. Previous experiences with cable concrete chutes have shown that the hydraulic jump forces have a large impact on the lower portion of the chute and the apron. Eye witness reports on early installations reported the apron section mats to be "flopping around" during a flow event. We are not aware of any model study based recommendations to address these hydraulic jump forces. Although anchors had been used on the chute portion of the structure, designers began specifying them in the apron area to try to hold down the blocks to maintain contact with the subgrade. The design of the anchors is subjective.

Several different approaches were used to look at the expected stability of the blocks.

1. Cable Concrete Chute Experience in Minnesota, Becker, 2003
2. Hydro Review, April, 1991, Clopper, Paul E.
3. NRCS Technical Supplement 14L, Use of Articulating Concrete Block Revetment Systems for Stream Restoration and Stabilization Projects.
4. A Technical Report Prepared for West Lorne Precast, by Dr. J.A. McCorquodale, Mr. M.S. Mohamed, and Mr. T.J. Faas.
5. Factor of Safety against sliding

Cable Concrete Chute Experience in Minnesota, Becker (2003). This paper was used as the design procedure for subject chute. The paper focuses on hydraulics but also recommends that the block sizes be based on providing a block critical shear stress twice that of the design shear stress. This factor of safety of 2 was based on addressing the unknown forces exerted on the blocks by the hydraulic jump. Based on this recommendation for the 6/11/08 event of 165 cfs the CC35 blocks used in the chute was adequate since, 2* 7.39 lb/ft2 = 14.78 lb/ft2; which is less than the 20.0 lbs/ft2 recommended by the International Erosion Control Systems recommend stress listed in Table 4. Becker's recommendation was not intended to verify the stability of a single block but the entire mat.

Hydro Review, 1991 The April, 1991 edition of Hydro Review contained the article, Protecting Embankment Dams with Concrete Block Systems, by Paul E. Clopper. This was the first adaption for ACB design of the "factor of safety" method used in riprap design. The major adjustment to the equations is to use known block geometry for the moment arms rather than an appropriate angle of repose. Using this procedure results in the following factor of safeties for the two events:

	Factor of Safety	
Event	2.5:1 Side Slope	100:1 Side Slope
6/7/05	2.49	6.46
6/11/08	2.17	5.56

Table 5, Factor of Safety, Hydro Review, 1991

Factors of safety were computed using a 2.5:1 and a 100:1 side slope. Structure was designed with 2:1 side slopes but as-built side slopes average out to ~2.5:1. The 100:1 is an attempt to only analyze the failed bottom blocks since they are not affected by the steepness of the side slope.

This procedure assumes a flush surface to the blocks. It does not consider water forces acting on a protrusion of the block above the assumed top of block plane. It is unrealistic that no block protrusions would exist and therefore we do not recommend that this method be used.

NRCS Technical Supplement 14L. TS-14L was published in 2007 and was primarily written by D. Wade Anderson, who at the time was a Design Engineer, with the NRCS in Ft. Worth, TX. The supplement has its roots in the manual, Design Manual for Articulating Concrete Block Systems, Harris County Flood Control District, TX. It is a current revision of the procedure introduced by Clopper in the '91 Hydro Review. One of the major revisions incorporated was the addition of water forces acting on a protrusion of blocks above the assumed top of block plane.

Since the failed blocks were on the bed of the chute, a spreadsheet version of the factor of safety formula found in TS-14L was modified to eliminate the side slope considerations. Inputting the as-built parameters for both the 6/7/05 and 6/11/08 events results in the following factors of safety:

Event	Flush	.5" Protrusion	1" Protrusion
6/7/05	3.05	1.50	0.99
6/11/08	2.57	1.19	0.78

Table 6, TS-14L Factor of Safety, Bed Blocks

Only the flush placements (0" protrusion) would meet the TS-14L recommended factor of safety of 1.5 for the 6/11/08 event. As stated previously, it is unrealistic that no block protrusions would exist. This analysis shows that a ~1" protrusion would have resulted in a FS < 1.0 for the 6/7/05 event, indicating a failure.

A Technical Report Prepared for West Lorne Precast.
This report was produced for West Lorne Precast, a manufacturer of cable concrete blocks in Canada. The report extracts figures and tables from the paper, "Hydraulic Model Studies of Cable Concrete Mats" performed at the Industrial Research Institute of the University of Windsor, Canada. The report lists acceptable velocities versus block type for horizontal placement and then factors in a velocity reduction factor based on the slope of the channel. It does this for unexposed and totally exposed conditions depending on how much of the leading edge of the mat is exposed to the jet of water.

The following table summarizes the report, interpolating between the recommended velocities of the unexposed (0" protrusion) and exposed (4.5" protrusion) conditions for the CC-35 block.

	Protrusion					
	Unexposed 0"	.5"	1"	1.5"	2"	Exposed 4.5"
Horizontal Placement	18.7					9.7
14.47^{o} slope	15.8	15.0	14.2	13.3	12.5	8.2

Table 8, Recommended Velocity (ft/sec), CC-35 Block,
from, A Technical Report Prepared for West Lorne Precast

The above table shows that the velocity from the 6/11/08 event (14.6 ft/sec) event exceeds the recommend velocity with a 1" protrusion and that the 6/7/05 event velocity (12.7 ft/sec) exceeds that recommended with a 2" protrusion. This method most likely incorporates a factor of safety which results in a lower recommended velocity than that at the time of failure.

Factor of Safety (FS) against Sliding

Sliding was checked by comparing the driving forces on an individual block to the resisting forces. Driving forces were approximated by applying the shear stress from the flow on to the area of the block plus the additional force from flow against the block protrusion. Resisting forces are friction between the geotextile attached to the bottom of the block and the subgrade. Uplift forces caused by flow over the block and against a protrusion are subtracted from the normal force creating the friction force.

For the 6/7/05 event, FS = 0.59 when only considering the driving forces caused by the shear stress and not even factoring in protrusion forces. Since FS < 1.0, the blocks can be assumed to not be stable by themselves during this flow event and that the cables are put into tension. A typical factor of safety against sliding is 1.5.

Sliding is not considered in the design methods based on Clopper's published works. This is because with most ACB systems the blocks are placed in intimate contact with each other and therefore the entire mat resists sliding. There is slack inherently built into the cable concrete system at the connections between the mats and between the blocks themselves which allow sliding to occur.

Subgrade.

The subsidence along the crest of the spillway and the presence of void spaces under the geotextile are indications that the subgrade is eroding. Erosion under the concrete mats is a documented concern. The Guide For The Design And Placement of Cable Concrete Mats by Dr. J. A. McCorquodale, University of Windsor, Ontario, CA states:

> "Another serious problem that can lead to failure on steep slopes in the 'piping' failure of the subgrade; water seeping through the geotextile along with groundwater flow can erode soil from under that geotextile possible opening a rill and then a channel into which the mats will collapse. A well designed drainage system with properly sized backfill material is essential for these channels"
>
> And
>
> "The design of subsurface drainage for long steep channels with supercritical flow requires the input of an expert. The drainage on these slopes is necessary to prevent erosion or sloughing of the subgrade. This erosion may occur as a 'piping' failure or a sloughing type failure due to the fluidization of the subgrade material. The flow that lead to the potential failure may come from seepage though the geotextile under that mats or from groundwater flow."

The above reference refers to the subgrade erosion as 'piping'. This is probably not the correct definition in NRCS terminology as the NRCS has traditionally defined 'piping' as the movement of soil particles at the discharge face of a soil, due to a high seepage rate. The NRCS would identify soil movement from flow against a soil as erosion.

Investigation of the subgrade soils on the subject chute indentified them as CH clays with a PI of approximately 40. NRCS Technical Release 25 (TR-25) shows that the allowable velocity for soil lined channels increases with the soils PI, leveling off at a PI of 20. TR-25 is intended for flow in an open channel and therefore does not directly address flow conditions under the geotextile of cable concrete mats, but because of a CH soil's high PI, it suggests that it would be erosion resistant. TR-25 shows the allowable velocity on a soil to also be dependant on the suspended sediment load in the water. Flow against the subgrade would be entering through the geotextile and therefore would have a low sediment load. Per TR-25, this decreases the allowable velocity. The block stability analysis preformed in the previous section indicated that the blocks would most likely be unstable during the flow events listed. This would create a larger flow area under the blocks and consequently higher velocities that would cause erosion.

The possibility of seepage from the face of the chute slope causing the soil to become more erosive was suggested by members of the failure committee. This phenomenon is listed in TS-14L as one of the conditions which may lead to failure. No seepage was evident during the site investigation but that does not rule out the possibility of this occurring. The channel grade upstream of the chute was constructed with a positive grade but is now negative for several hundred feet upstream of the chute indicating erosion but more importantly creating ponding conditions which would add some additional head to seepage through the face of the chute slope. Many of the design guides for articulated concrete block stress the importance of a drainage layer under the blocks. The design guides state that this drainage layer is important for allowing pressure relief to occur. This drainage layer would have two additional purposes. The first would be to prevent the flow down the chute from pulling soil up between the blocks assuming the drainage layer was designed to meet filter requirements (geotextile is used to for this purpose). The second purpose would be to provide an erosion resistant material under the blocks if it was designed as such.

The author visited another cable concrete chute in Washington Co., MN, in July of 2008 and found evidence of rill erosion under the blocks with the blocks subsiding into the rills. In spite of the erosion under the chute, the mat of blocks is still intact. Similar design methods were used on this chute.

Conclusions

The failure of the chute armor on this site was caused by undersized block being used.

Analysis of this chute during the smaller 6/7/05 event suggests that a combination of sliding and overturning created an unstable condition for the blocks. NRCS Technical Supplement 14L shows that a protrusion of approximately 1" existed, resulting in the overturning of the floor blocks. An as-built protrusion of 0.5" is usually assumed in the ACB industry for design. A protrusion of 1" in a 4.5" thick block after construction seems excessive and unlikely, however due to the amount of slack inherent to the cable concrete system, it is plausible that a 1" protrusion was created by the blocks sliding and subsequent mat buckling.

Past observations of the bottom part of the chute "flopping around" are probably due to undersized blocks being used. The forces on the blocks due to the hydraulic jump are most likely not greater than those experienced on protruding blocks in the chute, however, due to the turbulent nature of a hydraulic jump, these forces would not be constant, creating a pulsating loading condition that allowed the blocks to flop around. This flopping around could have caused a flexural fatigue failure of the connecting cable system. Failure of the cable system would allow further lifting of the mats. This would dramatically increase the amount of protrusion and the related forces could cause tension failure of the cables.

A possible contributing factor in the total failure of the chute armor was erosion of the subgrade. Subgrade erosion could have altered the moment arms of forces acting on the blocks as assumed in the stability analysis and increased the momentum forces if the block protrusion increased. The erosion may have been made worse by the movement of the blocks, but since erosion was evident in the upper regions were there was no evidence of block movement, we suspect that erosion was occurring under assumed stable blocks. A possible contributor to flow under the lifted blocks is that through the deadman anchor geotextile penetrations. This would be at a much higher rate than through the geotextile.

The two design guides (Cable Concrete Chute Experience in Minnesota, Becker (2003) and Hydro Review, 1991) that suggest the blocks were sized appropriately should not be used due to failure of this chute and arguable methodology. A combination of The design guide, NRCS Technical Supplement 14L should be considered state of the art for Minnesota NRCS applications of articulated concrete blocks.

Recommendations

It is recommended that the block sizing procedure used in Cable Concrete Chute Experience in Minnesota, Becker (2003) and Hydro Review, 1991) not be used. The Becker paper should still be used for computing chute hydraulics but not the size of the blocks.

It is recommended that the definition of failure identified in Federal Highway Administration (FHWA) RD-89-199 (Clopper 1989) and summarized in NRCS Technical Supplement 14L be the basis of design. This definition states that failure is considered to be the local loss of intimate contact between the ACB and the subgrade. Once this occurs, the subgrade is subject to erosive forces. Chute clamps and anchors should be viewed as an additional factor of safety.

It is recommended that a combination of NRCS Technical Supplement 14L and a sliding analysis be used in the design of the blocks. An assumed protrusion of 0.5" would normally be used for this for design. It is suggested to approximate this by just using the TS-14L procedure with a minimum 1" of protrusion and a minimum factor of safety of 1.5 if a crushed rock subgrade is used immediately under the block/geotextile system.

A redesign of the chute must pass the design Q_{100} discharge of 366 cfs. With the current chute geometry the maximum velocity, V_{100} = 17.35 and the associated shear stress = 8.86 lb/ft^2. The largest standard sized cable concrete block is the CC-70 block. Utilizing this block assuming a 1" protrusion results in a factor of safety, FS = 0.98 which is unacceptable since it is less than 1.50. Using the oversized block CC-65-OS, a factor of safety of FS = 1.99 can be achieved with a 1" protrusion. These blocks weigh 490 lbs each and are 6.5" high with a base of 31.6" square. This analysis is based on the accepting the Cable Concrete's "critical shear stress" value as the "critical shear stress for block on a horizontal surface" listed in TS-14L.

It is recommended that the chute be reconstructed using the CC-65-OS blocks. A drainage layer should be installed on the chute's slope portion between the bottom geotextile and the geotextile attached to the bottom of the blocks. The drainage layer should be poorly graded crushed rock, 2-3 inches in diameter. Other types of drainage systems may be considered as long as the factor of safety against sliding is addressed. An additional factor of safety could be provided by flattening the chute. Clamps connecting the mats should be provided at every possible connection point to minimize the slack in the system. Longer u-bolts may be required to clamp some of these locations. Anchors should still be used at the same density as before. A different anchoring system may need to be considered because of potential difficulties in pushing the currently used deadman anchors through the drainage layer and eliminating slack..

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